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(54) **DIAMOND ELECTRODE NANOGAP TRANSDUCERS**

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CPC G01N 27/30; G01N 27/308; H01B 1/04; H01B 1/18; H01B 1/24
USPC 204/403.01–403.15, 409, 242; 205/777.5, 792; 422/82.01
See application file for complete search history.

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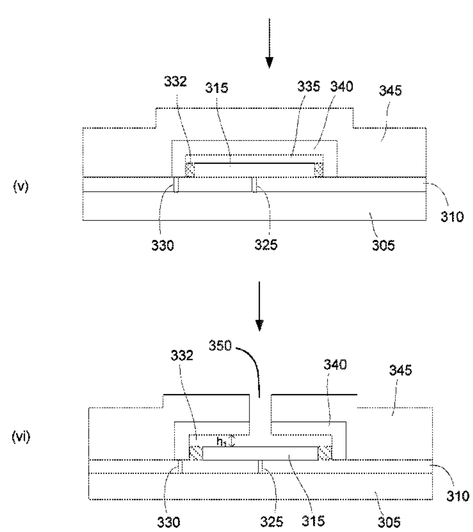
(57) **ABSTRACT**

Embodiments of the invention provide transducers capable of transducing redox active chemical signals into electrical signals. Transducers comprise two electrodes separated by a nanogap. At least one electrode is comprised of conducting diamond. Methods of fabricating nanogap transducers and arrays of nanogap transducers are provided. Arrays of individually addressable nanogap transducers can be disposed on integrated circuit chips and operably coupled to the integrated circuit chip.

24 Claims, 8 Drawing Sheets



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B82Y 15/00	(2011.01)

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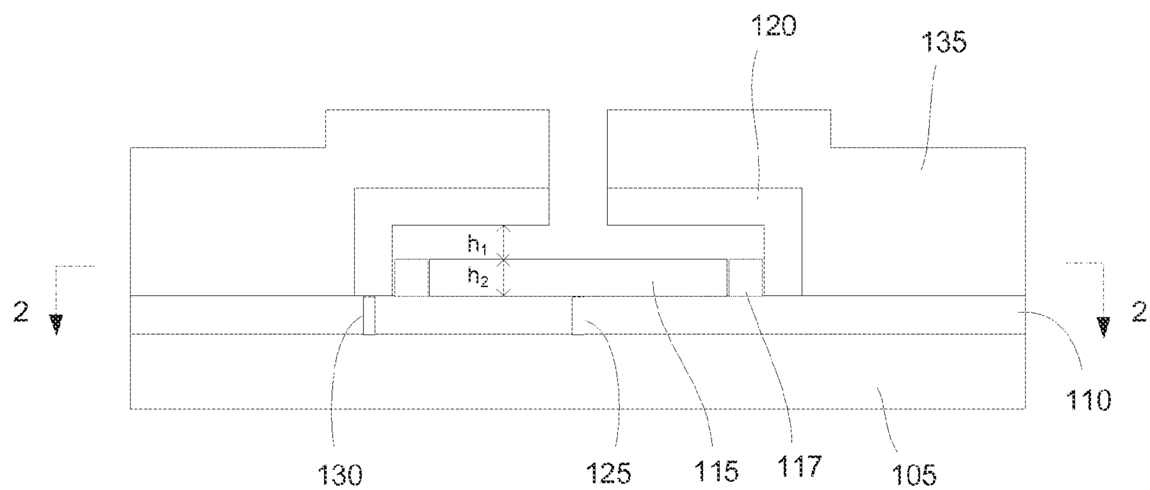


FIGURE 1

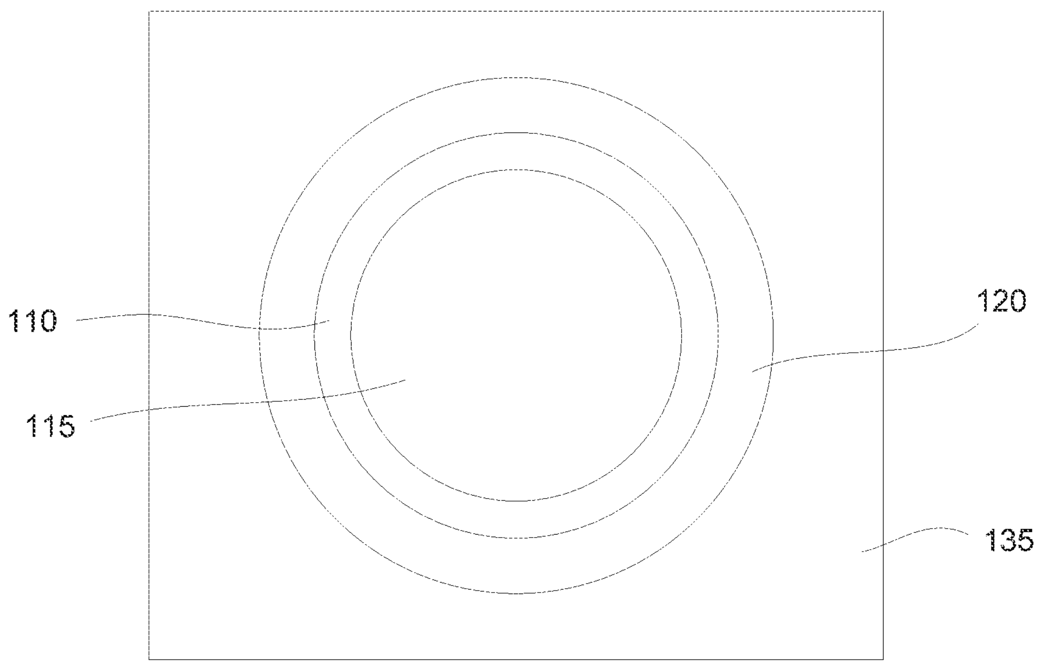


FIGURE 2

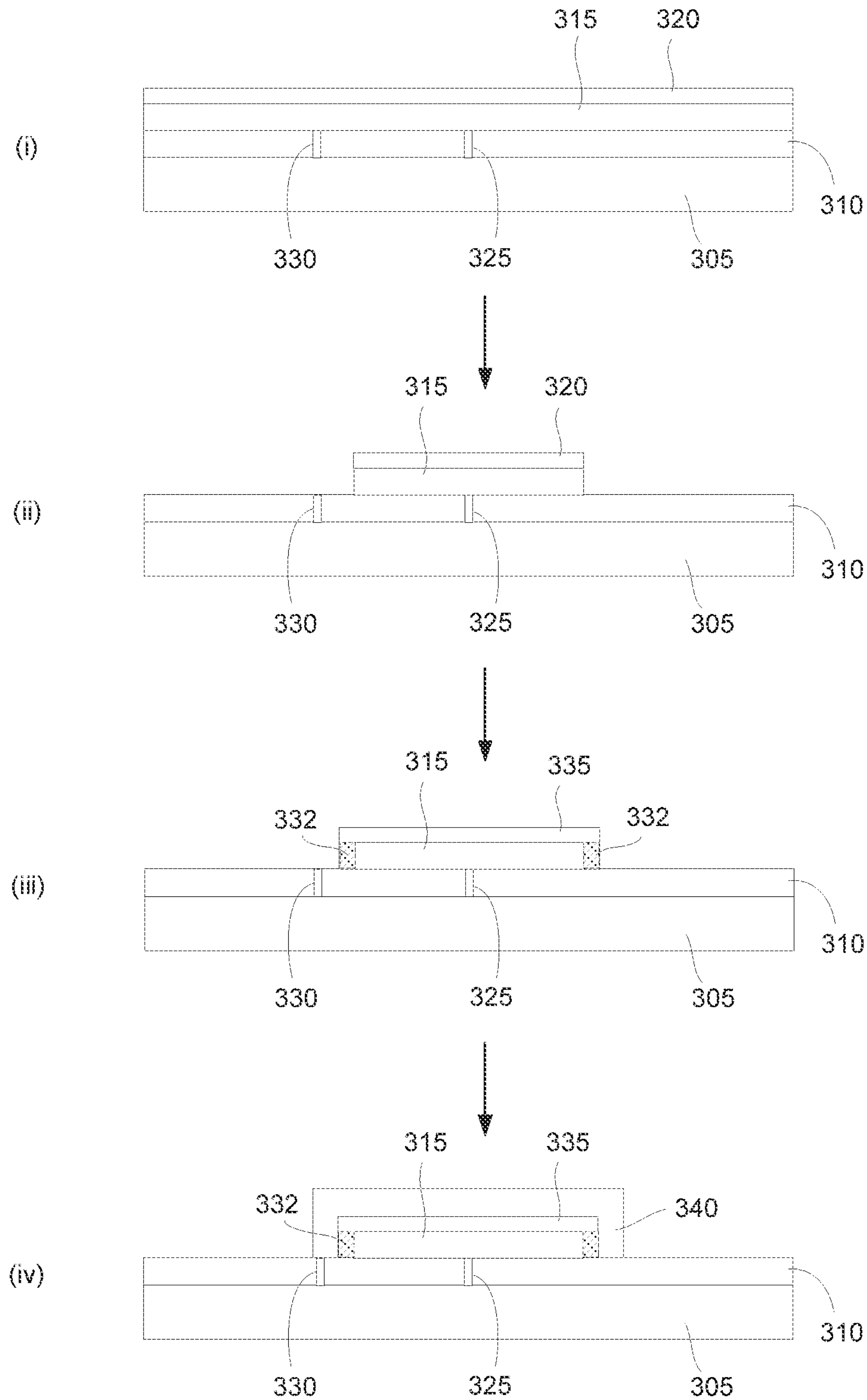
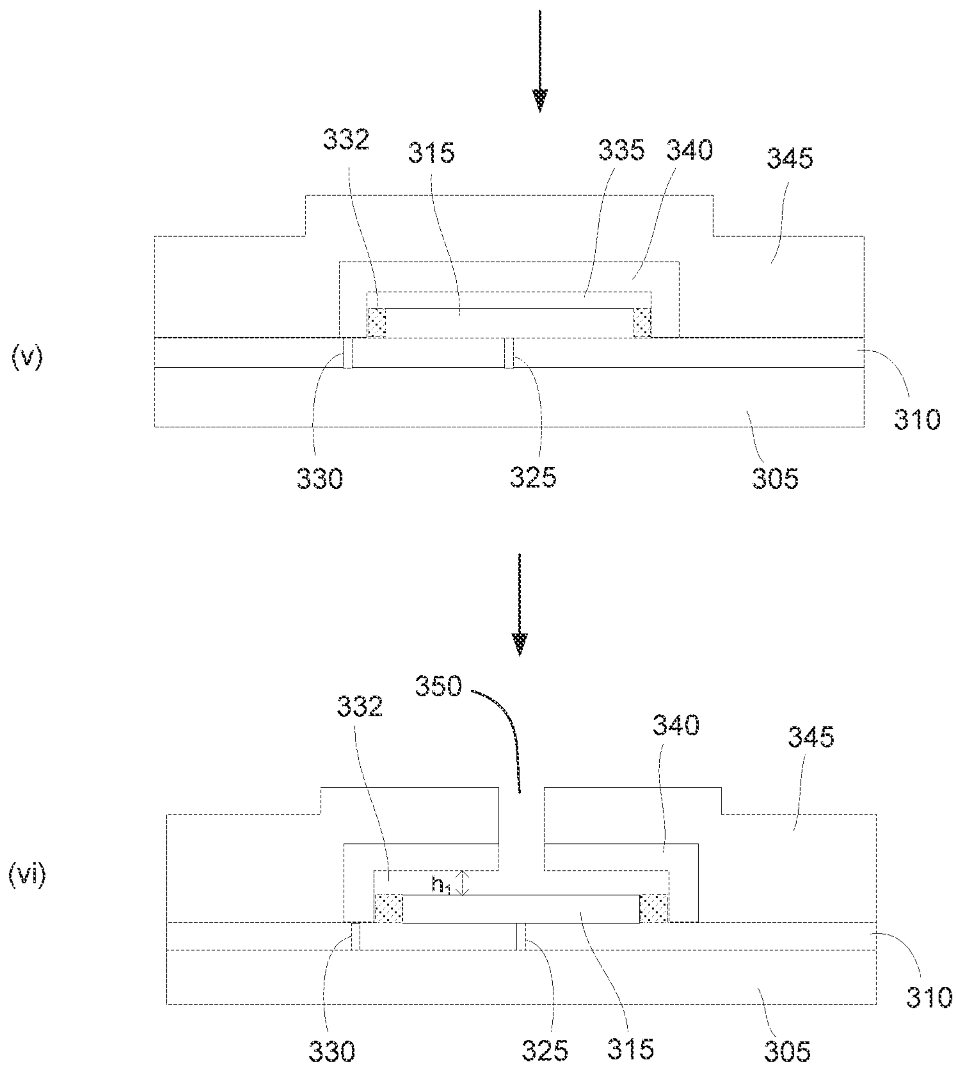
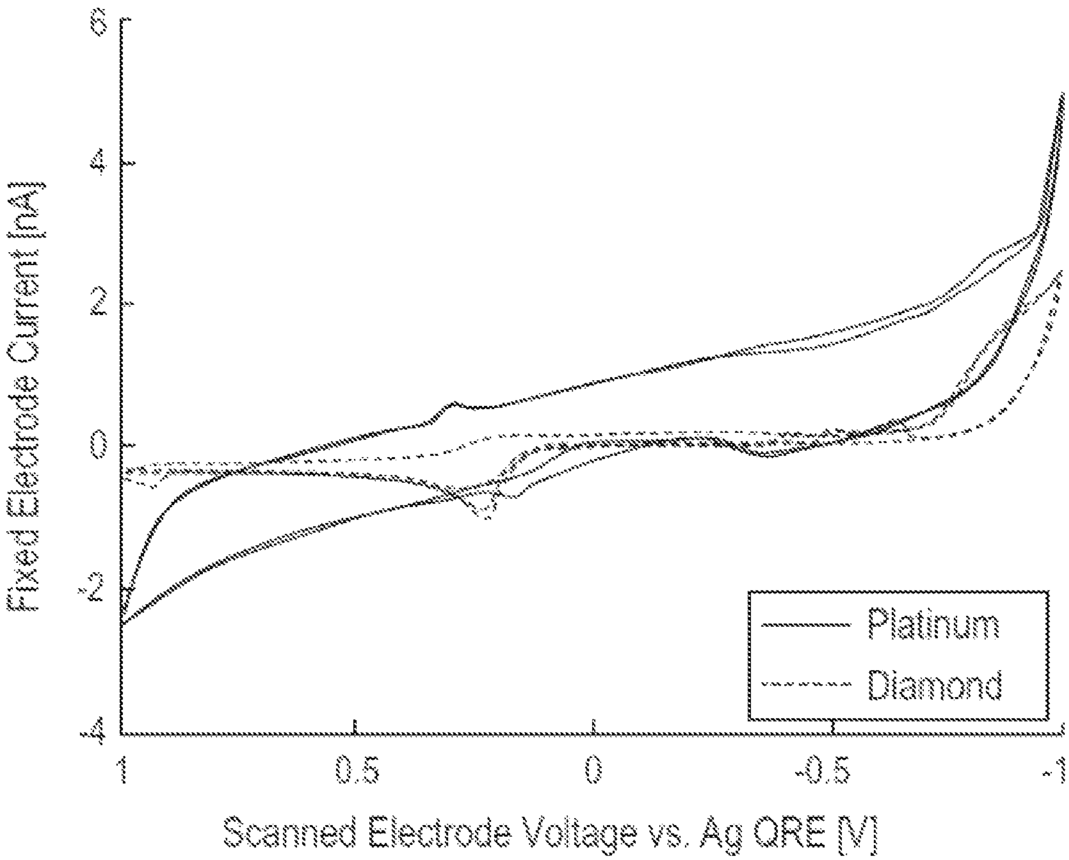

315
320
(i)
310
330
325
305
315
320
(ii)
310
330
325
305
315
335
332
332
(iii)
310
330
325
305
315
335
332
340
(iv)
310
330
325
305

FIGURE 3A



332
315
335
340
345
(v)
310
330
325
305
350
332
340
345
(vi)
h_1
310
330
325
315
305

FIGURE 3B



6
4
2
0
-2
-4
Fixed Electrode Current [nA]
1
0.5
0
-0.5
-1
Scanned Electrode Voltage vs. Ag QRE [V]
Platinum
Diamond

FIGURE 4A

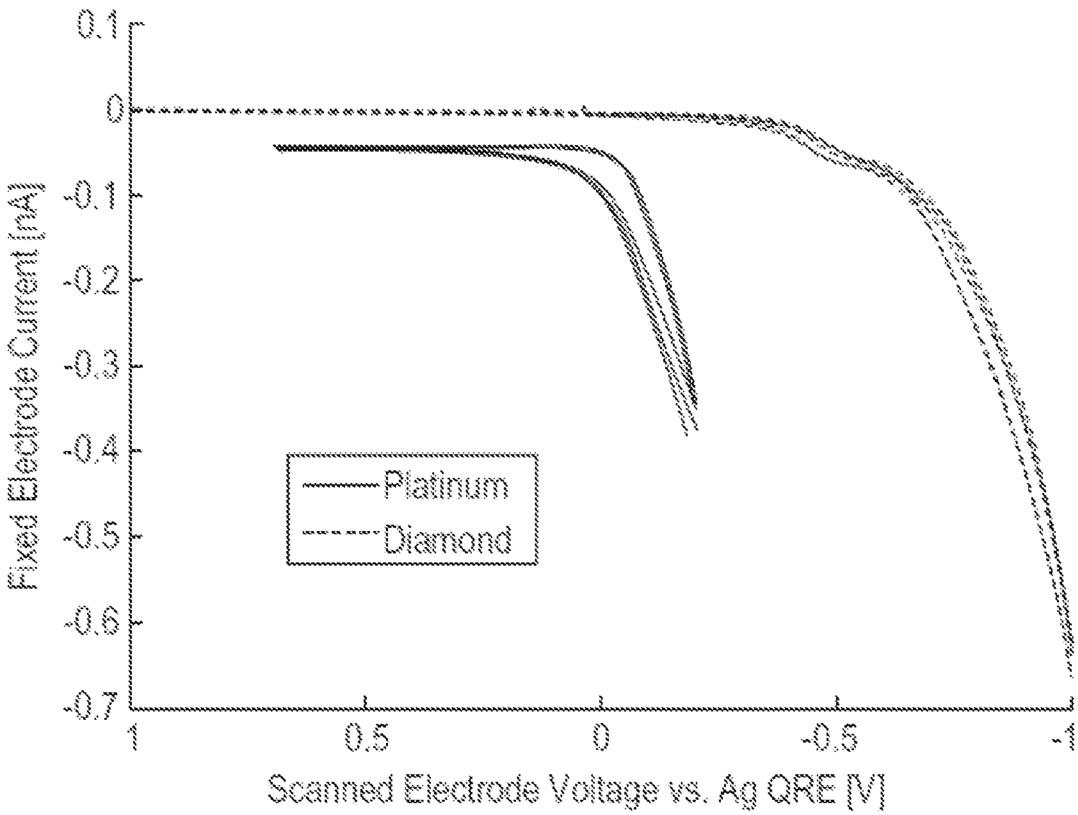

0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
Fixed Electrode Current [nA]
1
0.5
0
-0.5
-1
Scanned Electrode Voltage vs. Ag QRE [V]
Platinum
Diamond

FIGURE 4B

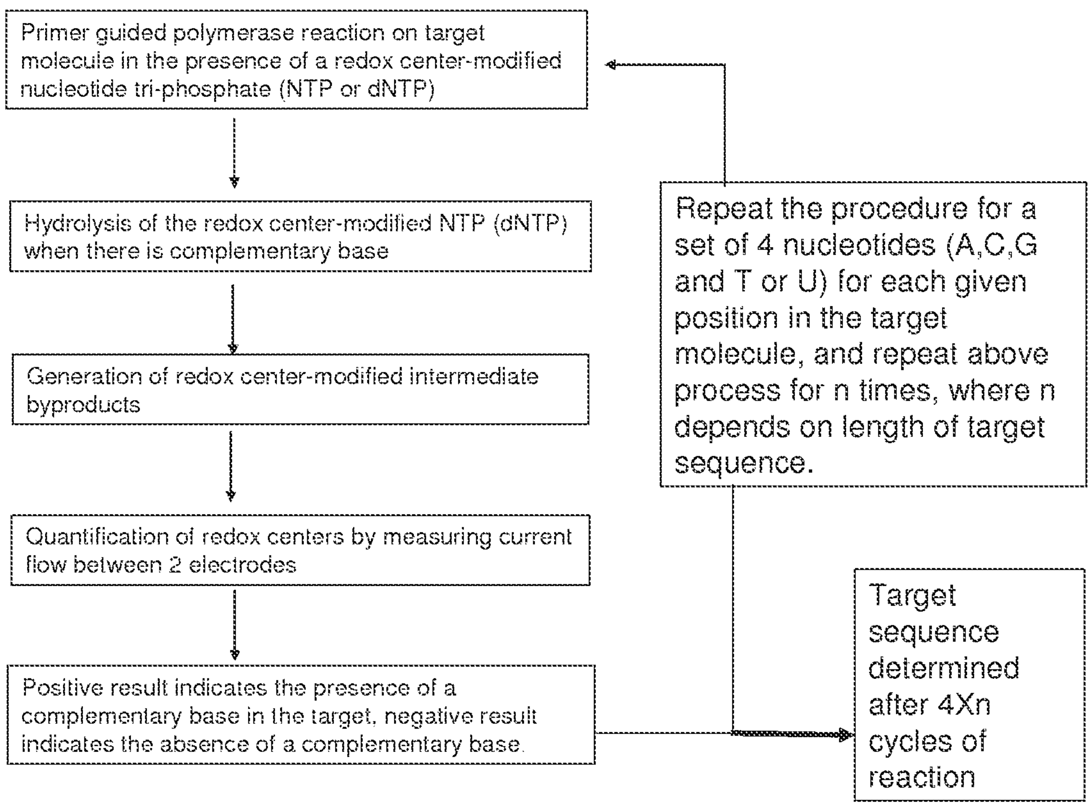
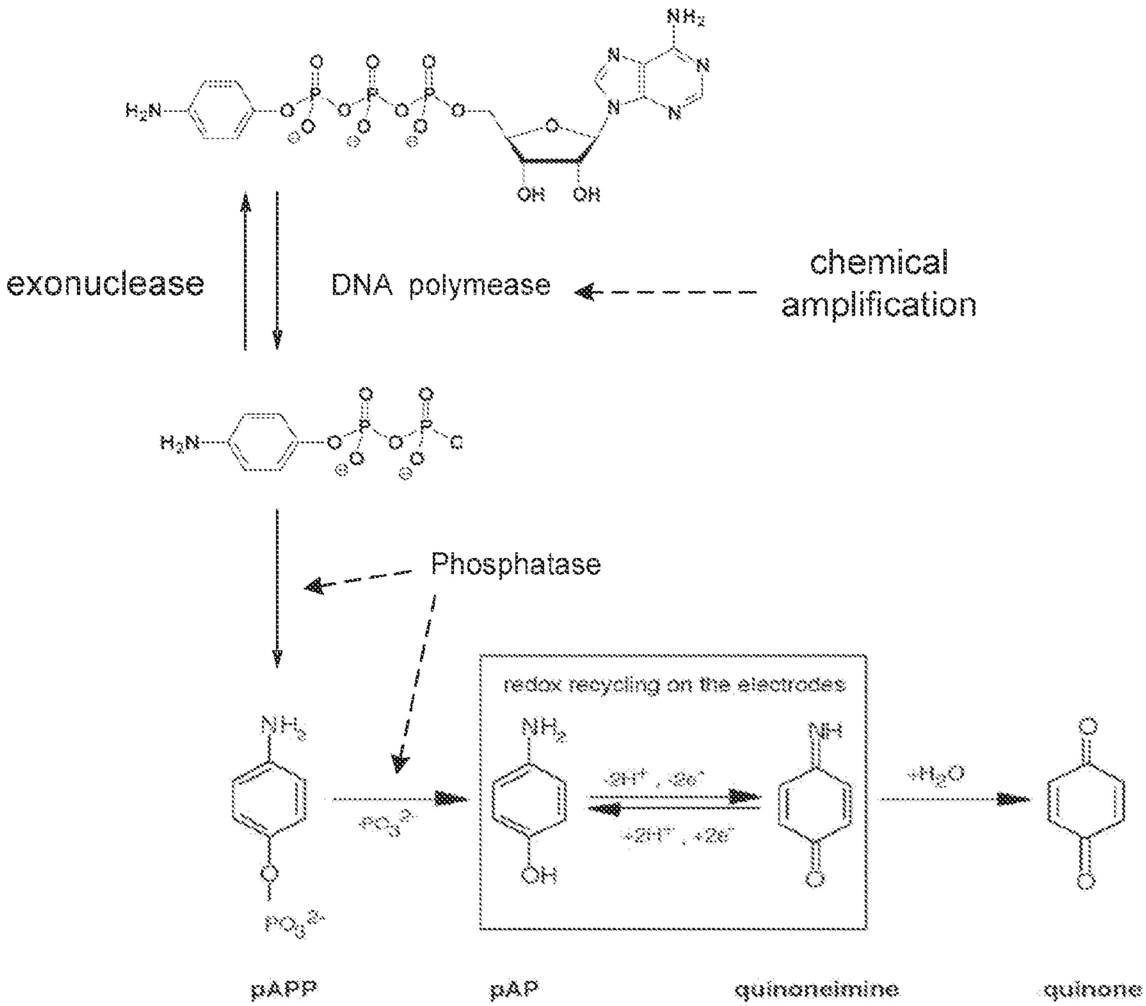

Primer guided polymerase reaction on target molecule in the presence of a redox center-modified nucleotide tri-phosphate (NTP or dNTP)
Hydrolysis of the redox center-modified NTP (dNTP) when there is complementary base
Generation of redox center-modified intermediate byproducts
Quantification of redox centers by measuring current flow between 2 electrodes
Positive result indicates the presence of a complementary base in the target, negative result indicates the absence of a complementary base.
Repeat the procedure for a set of 4 nucleotides (A,C,G and T or U) for each given position in the target molecule, and repeat above process for n times, where n depends on length of target sequence.
Target sequence determined after 4Xn cycles of reaction

FIGURE 5



exonuclease
DNA polymease
chemical amplification
Phosphatase
redox recycling on the electrodes
pAPP
pAP
quinoneimine
quinone

FIGURE 6

DIAMOND ELECTRODE NANOGAP TRANSDUCERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This present application is the U.S. National Stage of PCT/US2011/065154, filed Dec. 15, 2011, the contents of which are hereby incorporated by reference herein in its entirety.

The present application is related to U.S. application Ser. No. 12/655,578 entitled "Nanogap Chemical and Biochemical Sensors," filed Dec. 31, 2009, now pending, U.S. patent application Ser. No. 11/226,696, entitled "Sensor Arrays and Nucleic Acid Sequencing Applications," filed Sep. 13, 2005, now pending, which is a continuation-in-part application that claims the benefit of U.S. patent application Ser. No. 11/073,160, entitled "Sensor Arrays and Nucleic Acid Sequencing Applications," filed Mar. 4, 2005, and U.S. patent application Ser. No. 11/967,600, entitled "Electronic Sensing for Nucleic Acid Sequencing," filed Dec. 31, 2007 now pending, the disclosures of which are incorporated herein by reference.

FIELD OF THE INVENTION

The embodiments of the invention relate generally to transducers, nanogap transducers, electronic sensing, electrochemistry, redox cycling, and biomolecule detection.

BACKGROUND INFORMATION

Analytic devices that provide increased accuracy and/or robustness, decreased need for analysis sample, and/or high throughput are valuable analytical and biomedical tools. Additionally, molecular detection platforms that are miniaturized and manufacturable in high volumes provide access to affordable disease detection to many people in places and situations in which such access was not in the past possible. The availability of affordable molecular diagnostic devices reduces the cost of and improves the quality of healthcare available. Additionally, portable molecular detection devices have applications in security and hazard detection and remediation fields and offer the ability to immediately respond appropriately to a perceived security or accidental biological or chemical hazard.

Genetic information in living organisms is contained in the form of very long nucleic acid molecules such as deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Naturally occurring DNA and RNA molecules are typically composed of repeating chemical building blocks called nucleotides. The human genome, for example, contains approximately three billion nucleotides of DNA sequence and an estimated 20,000 to 25,000 genes.

Determination of the entire three billion nucleotide sequence of the human genome has provided a foundation for identifying the genetic basis of many diseases, such as cancer, cystic fibrosis, and sickle cell anemia. Sequencing the genomes or sections of the genome of individuals provides an opportunity to personalize medical treatments. The need for nucleic acid sequence information also exists in research, environmental protection, food safety, biodefense, and clinical applications, such as for example, pathogen detection, i.e., the detection of the presence or absence of pathogens and/or their genetic varients.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a schematic diagram illustrating a nanogap transducer.

FIG. **2** is a schematic diagram illustrating a view along **2-2** of the nanogap transducer of FIG. **1**.

FIGS. **3**A-B diagram a method for making a nanogap transducer having one or two electrodes comprised a conducting diamond material.

FIGS. **4**A-B graph cyclic voltammetric measurements for a nanogap transducer having a conducting diamond electrode.

FIG. **5** provides a flow diagram of a method for determining the sequence of a nucleic acid molecule.

FIG. **6** provides a reaction scheme showing a method for sequencing a nucleic acid molecule through the detection of an oxidation-reduction reaction of a redox active species.

DETAILED DESCRIPTION OF THE INVENTION

The ability to detect biological reactions and molecules at ultra-low concentrations has applicability to, for example, molecular detection and analysis, molecular diagnostics, disease detection, substance identification, and DNA detection and sequencing. Embodiments of the invention provide electronic sensors that are capable of detecting biological reactions and molecules and that exhibit high sensitivity, extremely reduced footprints, and a high degree of manufacturability. Nanogap transducers according to embodiments of the invention can be in the form of large arrays of nanogap transducers. For example, arrays of nanogap transducers comprising 1000 to 10 million or one million to 10 billion transducers in which 50% or more, 75% or more, 85% or more, 90% or more, 95% or more, or 98% or more of the transducers are functioning sensors are provided.

Embodiments of the invention provide transducers capable of functioning as electronic sensors and redox cycling sensors. In general, redox cycling is an electrochemical method in which a molecule that can be reversibly oxidized and/or reduced (i.e., a redox active molecule) moves between at least two electrodes that are biased independently, one below a reduction potential and the other one above an oxidation potential for the redox active molecule being detected, shuttling electrons between the independently biased electrodes (i.e., the molecule is oxidized at a first electrode and then diffuses to a second electrode where it is reduced or vice versa, it is first reduced and then oxidized, depending on the molecule and the potentials at which the electrodes are biased). In redox cycling the same molecule can therefore contribute a plurality of electrons to the recorded current resulting in the net amplification of the signal.

Nanogap transducers according to embodiments of the invention can be reliably fabricated in a CMOS (complementary metal oxide semiconductor) compatible manner allowing dense integration of sensor units (and optionally driving electronics) onto a single platform, such as for example a chip or silicon wafer typically used in integrated circuit manufacturing applications. Because the nanogap transducers provided by embodiments of the invention are very small and very sensitive, they provide the ability to detect molecules and biomolecules at ultra-low concentrations in a massively parallel manner. An individual nanogap transducer can, for example, occupy as little as 0.5 μm^2 on an array or other chip surface. In other embodiments an individual nanogap transducer occupies between to as 0.5 μm^2 to 50 μm^2 or 0.5 μm^2 to 100 μm^2 of area on an array or other chip surface. The ability to detect molecules in a highly sensitive manner has applications in fields of diagnostics, proteomics, genomics, security and chemical and biological hazard detection.

FIG. **1** illustrates a nanogap transducer that is capable of functioning as an electronic sensor, detecting redox molecules, and/or functioning as a redox cycling sensor. In FIG.

1, a substrate **105** has a dielectric layer **110** and first electrode **115**. A second electrode **120** is separated from the first electrode by a gap that has a height, h_1. In embodiments of the invention, the height of the gap, h_1, is less than 500 nm or between 10 and 200 nm, between 10 and 150 nm, or between 25 and 150 nm. Optional electronic interconnections **125** and **130**, such as vias through dielectric layer **110**, make connections to optional electronics (not shown) housed in the substrate **105**. In embodiments of the invention, the substrate **105** is an integrated circuit (IC) chip and comprises electronics for, for example, driving electrodes **115** and **120**, signal reading, signal amplification, and/or data output. The substrate can be other materials, such as, for example, glass, passivated metal, polymer, semiconductor, PDMS (polydimethylsiloxane), and/or flexible elastomeric substances. In embodiments in which the substrate does not house electronics, electrical connections to electrodes **115** and **120** can extend out along a surface of insulating layer **110** or through substrate **105**, although other configurations are also possible. An insulating layer **135** is proximate to second electrode **120**. The insulating layer **135** can be comprised, for example, of silicon dioxide, silicon nitride, silicon oxynitride, hafnium oxide, aluminum oxide, or, a polymer, such as polyimide. Other dielectric materials for insulating layer **135** are also possible.

The electrodes **115** and **120** are comprised of a conducting material, such as for example, diamond, platinum, and/or gold. In embodiments of the invention, at least one electrode **115** or **120** is comprised of a conducting diamond material. In embodiments of the invention, electrode **115** is comprised of conducting diamond. In further embodiments of the invention, both electrodes **115** and **120** are comprised of conducting diamond material. Diamond can be made to conduct electricity by doping it, for example. Dopants include, for example, boron, nitrogen, and phosphorous. In an embodiment of the invention, the dopant is boron. Doping concentrations for boron doped diamond materials include concentrations greater than 10^{20} atoms/cm^3 and less than 10^{22} atoms/cm^3. In embodiments of the invention, when the first electrode **115** is comprised of a conducting diamond material, the height of the electrode, h_2, is between 200 and 1000 nm. In alternate embodiments, the height of the conducting diamond electrode, h_2, is between 5 and 25 nm. In embodiments of the invention, the conducting diamond film is microcrystalline or nanocrystalline diamond. In further embodiments of the invention, optionally, a conducting diamond first electrode **115** has proximate dielectric regions **117**. The dielectric material can be, for example, silicon dioxide, silicon nitride, silicon oxynitride, or other electrochemically non-reactive material that is compatible with a manufacturing process. In operation, typically a reference electrode (not shown) is also used with the nanogap transducer. The reference electrode is in contact with the solution which is being measured but does not have to be located within the nanogap.

FIG. **2**, is a view along **2-2** of the nanogap transducer of FIG. **1**. The features of FIG. **2** are the same as those described with respect to FIG. **1**. Briefly, a first electrode **115**, a dielectric layer **110**, a second electrode **120**, and an insulating layer **135** are depicted. Other shapes are possible for electrodes **115** and **120**, such as, for example, oval, square, rectangular, triangular, or other multisided shape. Optional dielectric regions **117** are not shown in FIG. **2**, but would be located in the region labeled **110**.

FIGS. **3**A-B illustrate a method for making a nanogap transducer having a first electrode that is comprised of a conducting diamond material and optionally both a first and a second electrode that are comprised of a conducting diamond material. In FIG. **3**A, structure (i) comprises a substrate **305**, a dielectric layer **310**, a first electrode layer **315** comprised of a conducting diamond material, and a hard mask layer **320**. The conducting diamond material can be deposited, for example, using a hot filament CVD (chemical vapor deposition), a microwave plasma CVD, or a combustion flame assisted CVD process. The conducting diamond material can be deposited on a seed layer wherein the seed layer is deposited, for example by immersing the substrate in a solution that comprises diamond particles and attaching the particles to the surface using ultrasonication or by suspending diamond particles in a material that is spun onto the substrate surface. In embodiments of the invention, the conducting diamond material is boron doped diamond. In embodiments of the invention, the conducting diamond material is deposited with a boron doping concentration of greater than 10^{20} atoms/cm^3 and less than 10^{22} atoms/cm^3. In embodiments of the invention, the hard mask layer **320** is comprised of, for example, chromium or silicon dioxide. In embodiments of the invention, the substrate **305** is, for example, an IC chip comprising electronics for, for example, driving electrodes, signal detection, signal amplification, and/or data output. Optionally, conducting vias **325** and **330** are provided through the dielectric layer **310** to the substrate **305** that interconnect the electrodes with the optional electronics housed in the substrate **305**. Other materials are also possible for substrate **305**.

In embodiments of the invention, when the first electrode **315** is comprised of a conducting diamond material, it was found that it can be desirable to minimize the thickness of the first electrode in order to minimize the probability of shorting between the top and bottom electrodes. High aspect ratios for the first electrode were found to cause thinning of the sacrificial conformal coating at the edges of the electrode. However, it was also found that a minimum electrode height for the first electrode was necessary for microcrystalline diamond materials to avoid excessive surface roughness. It was found that excessive surface roughness of the first electrode could also cause openings in the sacrificial conformal coating and shorting between the first and the second electrodes. The height of the first electrode, when the first electrode is comprised of conducting diamond, in embodiments of the invention, can be between 300 and 1000 nm, between 300 and 800 nm, between 350 and 700 nm in order to balance height minimization with surface roughness considerations.

Structure (ii) of FIG. **3**A can be created by patterning the hard mask layer **320**, removing the hard mask layer **320** in unwanted regions, and etching the exposed diamond electrode layer **315**. The exposed diamond electrode layer **315** can be etched, for example, using an oxygen plasma. An elevated temperature, such as between 70 and 100 C, can facilitate the oxygen plasma etch. The hard mask layer **320** is then removed and optionally the first electrode **315** surface is planarized by depositing a dielectric layer, such as, for example, silicon dioxide or silicon nitride, and performing a chemical mechanical polish (CMP) on the first electrode surface **315**. The optional CMP process planarizes the electrode **315** surface and can improve the conformal coating properties of the following layers.

A conformal film of a sacrificial material **335** is deposited and patterned creating structure (iii) of FIG. **3**A. The conformal film of sacrificial material **335** can be patterned by first depositing a photoresist, patterning the photoresist, depositing the sacrificial material, for example, by sputtering or atomic layer deposition (ALD), and lifting off the photoresist to define the conformal film of sacrificial material in the desired regions (a liftoff process). In embodiments of the invention, the sacrificial material comprises chromium or tungsten. The conformal film of sacrificial material **335** can be deposited, for example, by sputtering ALD deposition to achieve a film that wraps around the bottom electrode **315**. In embodiments of the invention, the thin film of sacrificial material **335** has a thickness of less than 500 nm or between 10 and 200 nm, between 10 and 150 nm, or between 25 and 150 nm. In embodiments of the invention in which a dielectric layer is deposited and CMP is performed, optional dielectric regions **332** remain in the structure. In embodiments in which a dielectric layer is not deposited, regions **332** in structure (iii) of FIG. **3**A comprise the conformal film of sacrificial material **335**.

A second electrode material **340** is deposited on the conformal layer of sacrificial material **335** and patterned creating structure (iv) of FIG. **3**A. The second electrode material **340** can be patterned lithographically using a liftoff process. In embodiments of the invention, the second electrode material is conducting diamond. Conducting diamond can be deposited, for example, by seeding and then depositing the layer using a hot filament CVD, a microwave plasma CVD, or a combustion flame assisted CVD process. In embodiments of the invention, when the second electrode **340** material is diamond, the conformal film of sacrificial material **335** comprises tungsten. In further embodiments of the invention, the second electrode **340** is comprised of platinum or gold. The platinum electrode can be deposited, for example, by sputtering a thin layer of chromium (which can be about 10 nm thick) as an adhesion layer and then sputtering a layer of platinum. The gold electrode material can be deposited, for example, by sputtering, evaporation, electrodeposition, or electroless deposition processes. In embodiments of the invention, the sacrificial material **335** is tungsten when the second electrode **340** is comprised of gold.

A dielectric layer **345** is then deposited on the structure (iv) of FIG. **3**A, yielding structure (v) of FIG. **3**B. The dielectric material can be, for example, silicon dioxide, silicon nitride, silicon oxynitride, hafnium oxide, aluminum oxide, or a polymer, although other materials are also possible. An access hole **350** is created through the dielectric layer **345** and the second electrode **340**. The access hole **350** is created by defining a hole lithographically using a photoresist mask and then using a dry etching process to make the hole. The sacrificial material **335** is removed creating the gap between the first and second electrodes **315** and **340**. The sacrificial material **335** can be removed using a wet etch, for example, in the embodiments in which the sacrificial material **335** is tungsten or chromium. The resulting structure is shown in FIG. **3**B (vi). In embodiments of the invention, the height of the gap, h_1, is less than 500 nm or between 10 and 200 nm, between 10 and 150 nm, or between 25 and 150 nm. In embodiments in which a CMP process was used to planarize the first electrode **315**, regions **332** comprise a dielectric material, such as silicon dioxide, and in embodiments in which a dielectric deposition and CMP were not used, regions **332** are empty.

Dielectric materials also include, for example, silicon dioxide, silicon nitride, siliconoxynitride, carbon doped oxide (CDO), silicon carbide, organic polymers such as perfluorocyclobutane or polytetrafluoroethylene, fluorosilicate glass (FSG), and/or organosilicates such as silsesquioxane, siloxane, or organosilicate glass. Dielectric materials can also include polymers, such as, for example, polyimide.

FIGS. **4**A-B illustrate cyclic voltammetric graphs for a nanogap transducer having a conducting diamond first electrode and a platinum second electrode according to embodiments of the invention. It can be seen from FIGS. **4**A-B that it is possible to make operational nanogap transducers having a diamond electrode that do not exhibit first-second electrode shorting. In FIG. **4**A, the electrode current is plotted as a function of the electrode potential using a model compound (ferroscene) having a redox potential at about 0.240 V. Measurements were taken in phosphate buffered saline solution versus a silver wire reference electrode (Ag quasi-reference electrode (QRE).) Although a high background current is observed with the platinum electrode, advantageously it was found that the background current with the conducting diamond electrode was minimal. FIG. **4**B illustrates cyclic voltammetry measurements using a buffer solution with the nanogap transducer. The larger operational voltage window of the diamond electrode and significantly reduced background current compared to platinum electrode (diamond electrode registering dose to no current while platinum electrode has an offset current due to background current) can be seen from FIG. **4**B.

Because the background current with the conducting diamond electrode is small, it is possible to record measurements on small numbers of molecules using only one of the two working electrodes. Measurements can be recorded on as few as one molecule. In alternate embodiments, measurements recorded at both of the electrodes are used to generate the signal. A system for measuring and recording electrode potentials and current flow in nanogap transducers includes, for example, a bipotentiostat. Using a bipotentiostat, the potential of both electrodes versus the solution potential is controlled and the current flowing through the electrodes is measured. Some or all of the parts of a system for driving electrodes and measuring and recording current flow can be located in an integrated circuit (IC) chip that is electrically coupled to an array of individually addressable nanogap transducers housed on the IC chip. In embodiments of the invention, a computer system associated with the array of individually addressable nanogap transducers comprises software for measuring and recording electrode potential and current values using measurements from only one electrode where the electrode is comprised of conducting diamond. In alternate embodiments the computer system includes software for measuring and recording electrode potentials from two electrodes and/or both two electrodes and one electrode. Techniques such as electrochemical correlation spectroscopy can be used to produce a signal from measurements from two oppositely biased electrodes in a nanogap device.

In general, electronic sensors employing electrodes, such as nanogap transducers, are capable of measuring the impedance, the resistance, the capacitance, and/or the redox potential of the materials that are located on or near the electrode surface. The substrate on which the nanogap transducers reside may also include detection and/or drive circuits, logic for switching, latches, memory, and/or input/output devices. Optionally some or all of the electronics for sensing and driving electrodes and recording data are integrated circuits that are part of the substrate that houses an array of nanogap transducers. Electronics providing input and output control are optionally housed in the substrate, such as in an integrated circuit chip, or are provided through circuitry that is external the substrate. An array of nanogap transducers is optionally equipped with circuitry for individually addressing the electrodes, driving the electrodes at selected voltages, memory for storing voltage current information to be supplied to the electrodes, memory and microprocessors for measuring electrode characteristics, differential amplifiers, current-sensing circuits (including variants of circuits used in CMOS image sensors), and/or field effect transistors (direct and floating gate). Alternatively, one or more of these functions can be performed by external instruments and/or attached computer system(s).

In a redox cycling measurement, oppositely biased electrodes are used to repeatedly flip the charge state of redox active molecules in solution allowing each redox active molecule to participate in multiple redox reactions and thereby contribute multiple electrons to a measured current value. In redox cycling measurements, the height of the gap between the electrodes is on the nanometer scale. Redox active molecules in the cavity between the two electrodes shuttle multiple electrons between the electrodes, leading to amplification of the measured electrochemical current. Signals from the redox active species can potentially be amplified greater than 100 times, depending on factors such as the stability of the redox species and the ability of the redox species to diffuse out of the sensing region.

In embodiments of the invention, electrodes in the nanogap transducer are independently biased at the oxidation and reduction potential of the redox species to be detected. Redox species act as charge shuttles and the diffusion of the molecules from one electrode to the other results in the reduction and oxidation of the redox molecule and a net charge transfer. The magnitude of current through either electrode is proportional to the analyte (redox species) concentration in the cavity. The gaps between the electrodes are optionally sealed with beads to prevent the diffusion of the redox active species out of the cavity, thereby increasing the effective concentration of the redox species. Sealing of the cavity can prevent the escape of redox species from the cavity during sensor measurements.

In general, a redox active species is a molecule that is capable of reversibly cycling through states of oxidation and/or reduction a plurality of times.

In embodiments of the invention, nanogap transducers can be arrays of individually-addressable nanogap transducers. Arrays are built having a variety of dimensions and numbers of nanogap transducer. The selection of number layout of nanogap transducers is informed by factors such as, for example, the types and numbers of analytes to be detected, the size of the sensing regions, and costs involved in manufacturing the arrays. For example, arrays of nanogap transducers are 10×10, 100×100, $1{,}000\times1{,}000$, $10^5\times10^5$, and $10^6\times10^6$. Very high density, high density, moderate density, low density, or very low density arrays can be made. Some ranges for very high-density arrays are from about 100,000,000 to about 1,000,000,000 sensors per array. High-density arrays range from about 1,000,000 to about 100,000,000 sensors. Moderate density arrays range from about 10,000 to about 100,000 sensors. Low-density arrays are generally less than 10,000 cavities. Very low-density arrays are less than 1,000 sensors.

An array of individually addressable nanogap transducers can be housed on and electrically coupled to an IC chip. The IC chip is typically built on a semiconductor substrate, such as, a semiconductor wafer that is diced apart to yield individual IC chips. The base substrate on which an IC chip is built is typically a silicon wafer, although embodiments of the invention are not dependent on the type of substrate used. The substrate could also be comprised of germanium, indium antimonide, lead telluride, indium arsenide, indium phosphide, gallium arsenide, gallium antimonide, and/or other group III-V materials either alone or in combination with silicon or silicon dioxide or other insulating materials. Layers and layers comprising devices can also be described as the substrate or part of the substrate on which embodiments of the invention are housed or fabricated.

The nanogap transducer arrays allow, for example, a large number of immobilized DNA molecules to be sequenced simultaneously, although other uses are also possible. The immobilized DNA molecules can either be a sample to be sequenced or capture DNA probes of known sequence can be first immobilized and then the sample to be sequenced can be hybridized to the immobilized probes. The capture probes have a sequence designed to hybridize to sections of the sample DNA. In embodiments of the invention, DNA fragments (or capture probes) to be immobilized are diluted so that statistically each sensor has one DNA molecule immobilized. Sequence information is assembled from the nanogap transducers having a single DNA molecule immobilized. Information from nanogap transducers showing ambiguous results can be disregarded.

Methods are provided for sequencing nucleic acids in which amplification of the nucleic acid sample (i.e., increasing the number of copies of the nucleic acid molecules in the sample) optionally does not have to occur. FIG. **5** provides a flow diagram describing a method that is useful for sequencing a nucleic acid molecule, SNP (single nucleotide polymorphism) detection, and gene expression detection. In FIG. **5**, a nucleic acid molecule is attached to a surface inside an electronic sensor. A solution is provided to the sensor cavity containing a primer complementary to a section of the nucleic acid target. The primer DNA molecule hybridizes to a section of the DNA molecule attached inside the cavity and primes the attached DNA molecule for synthesis of a complementary strand of DNA. If the sequence of DNA inside the cavity is unknown, the primer might be one of many having random sequences provided to the DNA strand inside the sensor. The primer can be terminated with a nuclease-resistant nucleotide. After the primer is allowed to hybridize to the DNA molecule inside the cavity, a solution containing a DNA polymerase enzyme and a redox-center modified nucleotide triphosphate (NTP or dNTP) is added. The dNTP contains either a reodox modified deoxyadenosine triphosphate (dATP), deoxycytidine triphosphate (dCTP), deoxyguanosine triphosphate (dGTP), deoxythymidine triphosphate (dTTP), or uridine triphosphate (UTP). For example, if a redox-modified dATP has been provided and thymidine is the next complementary nucleic acid in the sequence, then the redox-modified dATP is incorporated into the growing DNA strand. Where there is a cytosine on the strand to be sequenced, a guanine will be incorporated, where there is a thymidine, an adenosine will be incorporated, and vice versa. If dATP is not the next complementary nucleic acid, then no chemistry occurs inside the sensor cavity. Products of the reaction are then detected. If no reaction has occurred, then the redox-center modified reaction products are not detected. Thus, a positive result (the detection of redox-center modified reaction products) indicates that dATP (in this example) is the next complementary nucleic acid in the growing chain. If a negative result is found, this method is then repeated for the three remaining redox-center modified nucleotides until a positive result is achieved to determine the identity of the complementary base. After the identity of a nucleotide has been determined, the growing strand of complementary DNA can be terminated with a nuclease resistant nucleotide.

FIG. **6** illustrates a method for sequencing a DNA molecule through chemically amplifying the redox signal obtained when a nucleotide base is complementary to the base provided by the template strand being sequenced. The method of FIG. **6** provides for chemical amplification of the signal when a complementary base in incorporated into a growing complementary strand. The primed growing DNA molecule is terminated with a nuclease resistant base through the action of a polymerase enzyme. In this example, the redox labeled NTP is γ-aminophenyl-adenine-triphosphate (dATP). The incorporation of a complementary redox labeled nucleotide into the growing strand releases the redox labeled pyrophosphate (PPi) group into solution. The action of a phosphatase enzyme removes the pyrophosphate from the redox molecule. Useful phosphatase enzymes include, for example, alkaline phosphatase, acid phosphatase, protein phosphatase, polyphosphate phosphatase, sugar-phosphatase, and pyrophosphatase. In this example, the redox active species is the p-aminopheonol (pAP) and quinoneimine pair. The number of p-aminopheonol molecules released into solution is amplified through the cycling of the redox labeled NTP incorporation and excision reactions. Specifically, a complementary redox labeled nucleotide is incorporated, an exonuclease enzyme removes the incorporated complementary nucleotide, and then DNA polymerase incorporates a second redox labeled complementary nucleotide and a second redox labeled pyrophosphate group is released into solution. Through these repeated cycles of incorporation and removal, the concentration of the redox active species builds up in solution. In this way, the signal resulting from the incorporation of a complementary base into the growing complementary strand is amplified. The removal of the phosphate groups activates the redox active species. The presence of the redox active species free of phosphate groups is detected electrochemically. The redox active species can be recycled between two electrodes of a nanogap transducer to amplify the signal further via a redox cycling reaction. As described more fully herein, the signal amplification technique of cycling redox active species between electrodes is referred to as redox cycling. By moving between electrodes of a nanogap transducer, each redox active species contributes multiple electrons to the measured current, thereby amplifying the measured current. If the nucleotide supplied to the reaction is not complementary to the growing DNA strand, then the free redox active species is not detected. Once a nucleotide incorporation has been detected, the growing strand is provided with a nuclease-resistant base that is complementary to the next space in the template DNA molecule that is being sequenced.

A redoxigenic nucleotide has a redox active species attached to the γ-phosphate group of the nucleoside. The base for the redoxigenic nucleotide may be an A, G, C, or T. Redox active species include, for example, aminophenyl, hydroxyphenyl, and/or napthyl groups. A redox active species may also be attached to the nucleotide base. The base may be an A, G, C, or T and the redox active species may be, for example a ferrocene, an anthraquinone, or a methylene blue molecule. A third redox active group attachment motif includes one in which the redox active group is attached to the sugar group of the nucleotide base. For the sugar-attached redox-modified nucleotide, the base may be an A, G, C, or T and the redox active species may be, for example a ferrocene, an anthraquinone, or a methylene blue molecule.

Polymerases are available that can incorporate ribonucleotides or modified nucleotides into DNA, such as for example, the commercially available Therminator DNA polymerase (available from New England Biolabs, Inc., Beverly, Mass.) or genetically engineered DNA polymerase. See also, for example, DeLucia, A. M., Grindley, N. D. R, Joyce, C. M., *Nucleic Acids Research,* 31:14, 4:129-4137 (2003); and Gao, G., Orlova, M., Georgiadis, M. M., Hendrickson, W. A., Goff, S. P., *Proceedings of the National Academy of Sciences,* 94, 407-411 (1997). Nuclease-resistant nucleotides can be ribonucleotides or other modified nucleotides. Exemplary nuclease resistant bases that can be incorporated into growing DNA strands hut that are resistant to digestion by exonucleases (such as the 3' to 5' exonuclease active DNA polymerases or exonuclease I and III) include alpha phosphorothioate nucleotides (available from Trilink Biotechnologies, Inc., San Diego, Calif.). Additionally, ribonucleotides can be incorporated into a growing DNA strand by Therminator DNA polymerase or other genetically engineered or mutated polymerases, but the ribonucleotide bases are resistant to digestion by exonucleases, such as exonucleases I or exonuclease III (available from New England Biolabs). Exemplary nucleases that cannot digest these resistant bases include exonuclease I, nuclease III, and 3' to 5' exonuclease active DNA polymerases.

In embodiments of the invention, a single nucleic acid molecule to be sequenced is attached to a surface inside a nanogap transducer. The nucleic acid is primed with a complementary strand that is terminated with a nuclease resistant nucleotide. A complementary redox-modified dNTP molecule is incorporated into the growing strand through the action of a DNA polymerase enzyme present in the solution in the nanogap transducer cavity. The electrodes of the nanogap transducer are oppositely biased at the redox potential of the redox species, and when the redox species is present, a current flow is detected at the electrode surfaces. The excess redox-modified dNTP from the polymerase reaction is washed away from the reaction site Any incorporated dNMP is then excised from the growing complementary DNA strand through the action of a nuclease enzyme present in the solution in the electrode cavity. This method is then optionally repeated for the three other nucleotides. Once the next complementary nucleotide has been determined, the growing complementary nucleic acid strand can be terminated with a complementary nuclease resistant base and the next complementary base can be determined.

In alternate embodiments, more than one copy of the nucleic acid molecule to be sequenced is attached in the electrode cavity. The attachment of a plurality of copies of the nucleic acid to be sequenced amplifies the signal detected when a complementary nucleotide triphosphate is provided to the cavity. The detected signal can then optionally be amplified further through redox cycling techniques.

Nucleic acid sequencing can be performed in a massively parallel manner using arrays of individually addressable nanogap transducers. A sample comprising nucleic acid molecules is presented to the array in a manner that results in statistically one nucleic acid molecule per reaction cavity. Electronics coupled to the reaction cavities detect the incorporation of nucleic acids in the cavities. Data from cavities that is inconsistent can be discarded. Sequence information for each nucleic acid in a cavity is built through multiple reaction cycles.

One or more surfaces of the nanogap transducer can be optionally functionalized with, for example, one of or combination of amine, aldehye, epxoy, thiol, groups, and molecules to be attached are functionalized with amine (for surface bearing carboxy, epoxy, and/or aldehyde functional groups) and carboxyl for surface bearing amine groups), thiol (for surface of gold) to facilitate molecular attachment. Various conjugation chemistries are available to join the functional groups (for example, EDC for amine-carboxyl). The concentration of molecules on the substrate surface is controlled, for example, in several ways: by limiting the density of surface functional groups or by limiting the quantity of molecules to be attached. DNA is immobilized on a surface, for example, by using acrydite-modified DNA fragments that are attached to a surface modified with thiol groups. Amine-modified DNA fragments can be attached to epoxy or aldehyde modified surfaces.

A sensor system including one or more arrays of nanogap transducers (such as an array of nanogap transducers on a IC device surface), electronics for driving the transducers and recording measurements, and a computer for recording an analyzing data, can also include fluid delivery systems that are capable of delivering fluids to the nanogap transducers. The fluidic system can comprise reservoirs for reagents, pumps and mixing chambers, washing solutions, waste chambers, and fluid delivery systems that deliver fluids to the surface of an array of nanogap transducers.

In general, the types of nucleic acids that can be sequenced include polymers of deoxyribonucleotides (DNA) or ribonucleotides (RNA) and analogs thereof that are linked together by a phosphodiester bond. A polynucleotide can be a segment of a genome, a gene or a portion thereof, a cDNA, or a synthetic polydeoxyribonucleic acid sequence. A polynucleotide, including an oligonucleotide (for example, a probe or a primer) can contain nucleoside or nucleotide analogs, or a backbone bond other than a phosphodiester bond. In general, the nucleotides comprising a polynucleotide are naturally occurring deoxyribonucleotides, such as adenine, cytosine, guanine or thymine linked to 2'-deoxyribose, or ribonucleotides such as adenine, cytosine., guanine, or uracil linked to ribose. However, a polynucleotide or oligonucleotide also can contain nucleotide analogs, including non-naturally occurring synthetic nucleotides or modified naturally occurring nucleotides.

Data from the sensors can be analyzed as follows. If a nanogap transducer has more than one DNA molecule attached within its cavity, there will be more than one possible reading from at least one of the sequenced positions. Therefore, only data from those nanogap transducers having one molecule attached in the nanogap transducer cavity (an effective sensor) are used in the sequence analysis. Sequences of effective sensors are aligned by computer program. The sequence information can be used as de novo sequencing information or reference sequencing information. Further analysis is performed depending on the quality of the data and purpose of the sequencing task.

Additionally, nanogap transducers according to embodiments of the invention are capable of performing a variety of biologically important detections which are not limited to those described herein. For example, nanogap transducers are capable of detecting mutations in DNA and identifying pathogens through DNA sequencing reactions. Additionally, electronic sensors are used to diagnose diseases through assaying metabolic enzyme activities. Pyrophosphate is a byproduct of many enzymatic reactions that are part of metabolic and signal transduction pathways. Nanogap transducers according to embodiments can be provided with recognition and binding sites for a target analyte. The nanogap transducer is created having the recognition and binding site of interest and a test is performed on a sample solution by exposing the sample solution to the analyte binding region of the biosensor device to allow binding of any specifically recognized biomolecules of interest. The nanogap transducer(s) can be integrated into micro- or nanofluidic systems that provides filtering and sample purification functions. Thus, an enzyme to be tested for functionality is bound in the electronic biosensor and a reaction solution is provided in which a reaction product is PPi labeled with a redox center. For example, a biosensor device probes the functionality of adenylating enzymes that convert fatty acids to acyl adenylate and produce PPi by binding the adenylating enzyme of interest in the biosensor device and providing fatty acid substrates as well as ATP in a reaction solution. Additional examples include catechols. In further examples, living microbes are specifically bound to biosensors. Microbes are optionally bound in the sensing device through an antibody that specifically recognizes a surface antigen on the microbe. Antibody sandwich assays are performed. In the antibody sandwich assay, an electronic sensor is provided having an antibody specific for the molecule to be detected, the sensor is exposed to the molecule to be detected, and a second antibody specific for a different epitope of the molecule to be detected is bound to the molecule to be detected. The second antibody has an attached molecule capable of converting redox labeled ATP to redox labeled PPi. The redox labeled PPi is detected through redox cycling. Redox labels include, for example, ferrocene, anthraquinone, and methylene blue molecules, and aminophenyl, hydroxyphenyl, and/or napthyl groups.

A computer or computer system comprises a processing system, including one or more processors that are communicatively coupled to one or more volatile or non-volatile data storage devices, such as random access memory (RAM), read-only memory (ROM), mass storage devices such as serial advanced technology attachment (SATA) or small computer system interface (SCSI) hard drives, and/or devices capable of accessing media, such as floppy disks, optical storage, tapes, flash Memory, memory sticks, CD-ROMs and/or digital video disks (DVDs). The term ROM refers to non-volatile memory devices such as erasable programmable ROM (EPROM), electrically erasable programmable ROM (EEPROM), flash ROM, and/or flash memory. The processor can also be communicatively coupled to additional components, such as graphics controllers, memory interface hubs, SCSI (small computer system interface) controllers, network controllers, network interfaces, and universal serial bus (USB) controllers. Some or all of the communications between elements of the computer system, additional processors, and/or external computers and computer networks can also occur using various wired and/or wireless short range protocols including, USB, WLAN (wireless local area network), radio frequency (RE), satellite, microwave, Institute of Electrical and Electronics Engineers (IEEE) 802.11, Bluetooth, optical, fiber optical, infrared, cables, and lasers. Typically a computer system is also coupled to other input/output devices, such as, for example, display screens, keyboards, trackpads, mice.

Persons skilled in the relevant art appreciate that modifications and variations are possible throughout the disclosure as are substitutions for various components shown and described. Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular, feature, structure, material, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention, but does not necessarily denote that they are present in every embodiment. Furthermore, the particular features, structures, materials, or characteristics disclosed in the embodiments may be combined in any suitable manner in one or more embodiments. Various additional layers and/or structures may be included and/or described features may be omitted in other embodiments.

We claim:

1. A device comprising, a substrate having a surface, and a transducer disposed on the substrate surface, wherein the transducer comprises:

a first electrode and a second electrode, wherein the first or the second electrode is comprised of conducting diamond, wherein the first and the second electrodes are each coupled to conducting lines through which voltage can be applied to the first and second electrodes independently and a current measured from each of the first and second electrodes independently, and wherein the first electrode has a face and the second electrode has a face and the face of the first electrode is separated from the face of the second electrode by a distance that is between 10 and 200 nm, a cavity capable of containing a fluid between the face of the first electrode and the face of the second electrode, and an access hole through the second electrode that is capable of allowing a fluid to enter and leave the cavity, wherein the substrate is an integrated circuit chip.

2. A device comprising, a substrate having a surface, and a transducer disposed on the substrate surface, wherein the transducer comprises:

a first electrode and a second electrode, wherein the first or the second electrode is comprised of conducting diamond, wherein the first and the second electrodes are each coupled to conducting lines through which voltage can be applied to the first and second electrodes independently and a current measured from each of the first and second electrodes independently, and wherein the first electrode has a face and the second electrode has a face and the face of the first electrode is separated from the face of the second electrode by a distance that is less than 500 nm, a cavity capable of containing a fluid between the face of the first electrode and the face of the second electrode, and an access hole through the second electrode that is capable of allowing a fluid to enter and leave the cavity, wherein the substrate is an integrated circuit chip and the first electrode and the second electrode are independently electrically coupled to electronics within the integrated circuit chip through the conducting lines.

3. The device of claim **2** wherein the conducting diamond is nanocrystalline diamond.

4. The device of claim **2** wherein the conducting diamond is boron doped diamond.

5. The device of claim **2** wherein both the first and second electrodes are comprised of conducting diamond.

6. The device of claim **2** wherein the first electrode is comprised of conducting diamond and the height of the first electrode is between 300 nm and 1000 nm.

7. The device of claim **2** wherein the first or the second electrode is comprise of gold or platinum.

8. The device of claim **1**, wherein the second electrode surrounds at least the face the first electrode and both sides of the first electrode.

9. The device of claim **2** wherein the face of the first electrode is separated from the face of the second electrode by a distance that is between 10 and 200 nm.

10. A device comprising, an integrated circuit chip having a surface, and an array of transducers disposed on the integrated circuit chip surface, wherein the array comprises at least 1000 transducers and at least 85% of the transducers are functional transducers, wherein transducers that make up the array are electrically coupled to and individually addressable through electronics in the integrated circuit chip, and wherein a transducer comprises: a first electrode and a second electrode, wherein the first or the second electrode is comprised of conducting diamond, wherein the first and second electrodes are independently coupled to the integrated circuit chip through which voltage can be applied to the first and second electrodes and a current measured from each of the first and second electrodes independently, and wherein the first electrode has a face and the second electrode has a face and the face of the first electrode is separated from the face of the second electrode by a distance that is less than 500 nm, a cavity capable of containing a fluid between the face of the first electrode and the face of the second electrode, and an access hole through the second electrode that is capable of allowing a fluid to enter and leave the cavity.

11. The device of claim **10** wherein the face of the first electrode is separated from the face of the second electrode by a distance that is between 10 and 200 nm.

12. The device of claim **10** wherein the conducting diamond is nanocrystalline diamond.

13. The device of claim **10** wherein the conducting diamond is boron doped diamond.

14. The device of claim **10** wherein both the first a second electrodes are comprised of conducting diamond.

15. The device of claim **10** wherein the first electrode is comprised of conducting diamond and the height of the first electrode is between 300 nm and 1000 nm.

16. The device of claim **10** wherein the first or the second electrode is comprise of gold or platinum.

17. A system comprising, a computer operably coupled to an integrated circuit chip wherein the integrated circuit chip comprises an array of transducers disposed on a surface of the integrated circuit chip, a fluidic system capable of supplying fluids to the surface of the integrated circuit chip comprising the array of transducers, wherein transducers that make up the array are electrically coupled to and individually addressable through electronics in the integrated circuit chip, and wherein a transducer comprises:

a first electrode and a second electrode, wherein the first or the second electrode is comprised of conducting diamond, wherein the first and second electrodes are independently coupled to the integrated circuit chip through which voltage can be applied to the first and second electrodes and a current measured from each of the first and second electrodes independently, and wherein the first electrode has a face and the second electrode has a face and the face of the first electrode is separated from the face of the second electrode by a distance that is less than 500 nm, a cavity capable of containing a fluid between the face of the first electrode and the face of the second electrode, and an access hole through the second electrode that is capable of allowing a fluid to enter and leave the cavity.

18. The device of claim **17** the face of the first electrode is separated from the face of the second electrode by a distance that is between 10 and 200 nm.

19. The device of claim **17** wherein the array comprises at least 1000 transducers and at least 90% of the transducers are functional transducers.

20. The device of claim **17** wherein the conducting diamond is nanocrystalline diamond.

21. The device of claim **17** wherein the conducting diamond is boron doped diamond.

22. The device of claim **17** wherein both the first and second electrodes are comprised of conducting diamond.

23. The device of claim **17** wherein the first or the second electrode is comprise of gold or platinum.

24. The device of claim **17** wherein the computer is configured to perform data analysis using current measurements from one of the first or the second electrode wherein the one of the first or second electrode from which the current is measured is comprised of conducting diamond.

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